arXiv:astro-ph/9909516v1 30 Sep 1999

Binarity of Central Stars of Planetary Nebulae

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Abstract. I list the 16 planetary nebulae (PNe) known to contain close-binary nuclei, and show that the nebulae generally have axisymmetric structures, including elliptical, bipolar, or ring morphologies. The orbital periods range from 2.7 hr to 16 days, and close binaries constitute ≈10% of all central stars. Since the known binaries were found mainly from photometric variability, which depends on heating effects at very small stellar separations, radial-velocity surveys will be necessary to find the large predicted population of binary nuclei with periods of about 10-100 days. Other PN phenomena that may arise from binary-star interactions include jets and point-symmetry, the periodically spaced arcs revealed by *HST* in the faint halos around several PNe and proto-PNe, and the existence of PNe in globular clusters. There is thus considerable circumstantial evidence that binary-star processes play a major role in the formation and shaping of many or even most PNe.

1. Introduction

The subtitle of this paper could be "Do close companions strongly influence, or even *cause*, the ejection of most planetary nebulae?" The answer to this question may well be "yes"—I certainly think it is—but as we will see the evidence is still incomplete.

I want to acknowledge the contributions of my collaborators in various portions of this work, including D. Alves, R. Ciardullo, M. Cohen, L. Fullton, M. Livio, K. Schaefer, M. Sipior, H. Van Winckel, and C.-Y. Zhang.

2. PNe with Known Close-Binary Nuclei

I begin by considering those planetary nebulae (PNe) where we *know* the central star is a close binary, because it (a) exhibits periodic photometric variability (due to actual stellar eclipses, or to heating effects on a main-sequence companion of the hot nucleus), (b) is a short-period spectroscopic binary, or (c) has a composite spectrum along with evidence of interaction between the two stars. There are 12 objects currently known in the first class, and one in the second (NGC 2436, first discovered as a spectroscopic binary, which also shows episodic periodic light variations). The third class contains three "Abell 35-type" planetary-nebula nuclei (PNNi), in which a cool, rapidly rotating optical star has a hot companion revealed in *IUE* UV spectra. All three A 35-type PNNi show low-amplitude

light variations with periods of a few days (e.g., 5.9 days for LoTr 5—Bond & Livio 1990; Strassmeier, Hubl, & Rice 1997), but these arise from starspots on the rotating cool stars, and the true orbital periods remain as yet unknown. The rapid rotation of the optical companions is believed to result from accretion of angular momentum from the wind of the AGB progenitor of the star that is now the hot PNN (e.g., Jeffries & Stevens 1996; Gatti et al. 1997, 1998). All 16 objects are listed in Table 1.

Table 1
Planetary Nebulae with Close-Binary Nuclei

Planetary Nebula	Central Star	Period (days)	Binary Type
Abell 41	MT Ser	0.113	Reflection
DS 1	KV Vel	0.357	Reflection
Hf 2-2	(MACHO var.)	0.399	Reflection
Abell 63	UU Sge	0.465	Eclipsing
Abell 46	V477 Lyr	0.472	Eclipsing
HFG 1	V664 Cas	0.582	Reflection
K 1-2	VW Pyx	0.676	Reflection
Abell 65	. . .	1.00	Reflection
HaTr 4	. . .	1.74	Reflection
(Tweedy 1)	BE UMa	2.29	Eclipsing
SuWt 2	. . .	2.45	Eclipsing
Sp 1	. . .	2.91	Reflection
NGC 2346	V651 Mon	15.99	Spectroscopic
Abell 35	BD −22°3467	. . .	*IUE* composite
LoTr 1	. . .	. . .	*IUE* composite
LoTr 5	HD 112313	. . .	*IUE* composite

Table 1 is similar to the one I presented at Asymmetrical Planetary Nebulae I (Bond 1995), with two main additions: the period of the eclipsing nucleus of SuWt 2 is now established as 2.45 days, from my recent CCD photometry at Cerro Tololo; and a new short-period reflection binary has been discovered in Hf 2-2 by the MACHO collaboration (Lutz et al. 1998).

As noted previously (Bond 1995 and references therein), the fraction of detectable close binaries among randomly selected PNNi is of order 10–15%. (This statement is based on the fact that the 13 variables of Table 1 were found in photometric surveys of somewhat more than 100 PNNi). In a recent analysis of the MACHO Galactic bulge database, Lutz et al. (1998) found one close binary (Hf 2-2, mentioned above) out of 22 random PNNi that fell within the MACHO survey area, giving a close-binary fraction of $4.5 \pm 4.5\%$. This is in tolerable agreement with the figure quoted above, given the small-number statistics.

The fraction of known very close binaries among PNNi is remarkably high. Moreover, the photometric search technique[1] reveals only binaries with short

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[1]Large-scale synoptic photometric surveys are, unfortunately, becoming almost impossible at the U.S. national observatories due to closures of small telescopes

periods ($\lesssim$ a few days), since it relies on eclipses and heating effects. It is thus quite possible that the short-period PNNi are only the tip of an iceberg of a substantial population of longer-period binaries.

But do we expect to find PNNi with longer binary periods? The binaries in Table 1, with periods of 2.7 hr to 16 days, are so close that the nebulae *must* have been ejected through common-envelope (CE) interactions (see Bond & Livio 1990; Iben & Livio 1993; Sandquist et al. 1998; and references therein). Several groups (e.g., de Kool 1990; Yungelson, Tutukov, & Livio 1993; Han, Podsiadlowski, & Eggleton 1995) have performed simulations in which they evolve a population of primordial binaries through the stage of formation of a red giant and, if the system is close enough, the subsequent ejection of a CE accompanied by a spiral-down of the orbit. The outcome of these syntheses depends on the efficiency parameter α_{CE}, which is the fraction of the orbital gravitational energy that goes into ejecting material from the envelope into space. For $\alpha_{\mathrm{CE}} \approx 1$ a substantial fraction of the resulting binaries will have periods of 10 to several hundred days. In that case, since the fraction of *short-period* binaries (with periods of ≈ 0.1 to 10 days) is already $\approx 10\%$, the *total* fraction of binaries could be quite large. On the other hand, if the crucial α_{CE} parameter is small, $\lesssim 0.1$, then the known short-period fraction could represent substantially all of the binaries that have emerged from CE interactions (other than those binaries that have actually coalesced).

Thus the most crucial next observational step in this subject would be a radial-velocity survey of PNNi for binaries with $10\,\mathrm{days} \lesssim P \lesssim 100\,\mathrm{days}$. The binary fraction in this range would provide a crucial constraint on the value of α_{CE}, and would tell us whether CE ejections are the primary way of making PNe.

3.   Morphologies of PNe Ejected from Common Envelopes

I now consider the morphologies of PNe which are *known* to have close-binary nuclei. Previously published papers have addressed this subject in detail (Bond & Livio 1990; Walton, Walsh, & Pottasch 1993; Pollacco & Bell 1997), and generally it is found that such PNe are axisymmetric, showing either elliptical or more pronounced butterfly or bipolar shapes. I showed a number of new ground- or space-based images at the workshop, but this printed version allows space for only a few examples of the most interesting classes of phenomena.

Non-spherical morphologies. These are ubiquitous among PNe known to have close-binary nuclei. Fig. 1, for example, shows ground-based images of the newly discovered (Liebert et al. 1995) PN around the eclipsing binary BE UMa, and of the PN A 41 whose central star is a binary with the extremely short period of 2.7 hr (Grauer & Bond 1983). BE UMa, where we know we view the binary orbit edge-on, shows a rectangular structure (probably an edge-on cylinder), and an apparent wind-blown bubble along an axis perpendicular to the presumed orbital plane on the upper left side. A 41 likewise shows bright structures on either side of the nucleus, again indicating a cylindrical morphology, and again with incipient wind-blown bubbles along the axis. The bipolar structure is even more pronounced in recent *Hubble Space Telescope* (*HST*) images of NGC 2346 (not shown), which has a classical butterfly morphology.
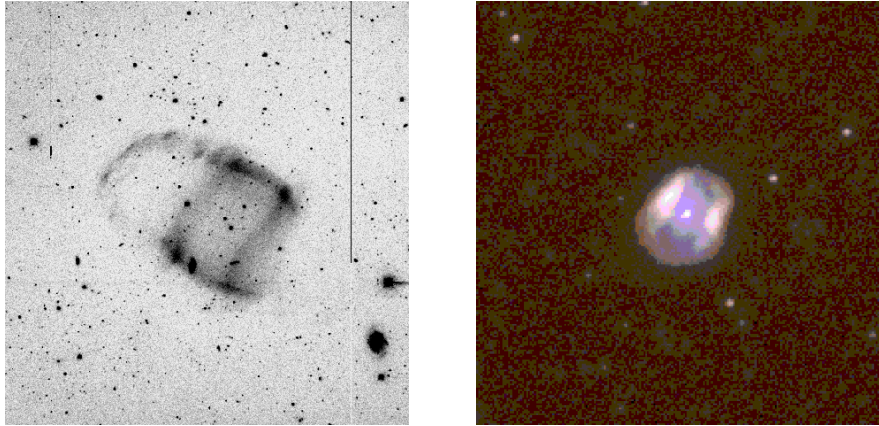
Figure 1.   Ground-based images of the BE UMa PN (**left**) and A 41 (**right**). The BE UMa image was taken in [O III] $\lambda 5007$ with the Kitt Peak 4-m, and the A 41 image is the sum of [O III] and Hα, obtained with the Cerro Tololo 0.9-m. Note the axisymmetric structure in both images, with wind-blown balloons at the poles.

Ring nebulae. By contrast, Sp 1 has a nearly circular morphology, as shown in the left-hand image of Fig. 2. We argued (Bond & Livio 1990) that Sp 1 is in fact a ring or cylinder (rather than a spherical structure), seen almost pole-on. This was in accord with the low photometric amplitude of the reflection effect in the central binary, which would indeed be small in a binary viewed close to pole-on. If so, we would expect to see other PNe around binary nuclei viewed at less extreme angles as ellipses rather than circles. Gratifyingly, SuWt 2 (Fig. 2, right-hand side) does show an elliptical shape, and the central star is an *eclipsing* binary. These "wedding-ring" PNe have extremely high "density contrasts" between their equatorial and polar regions.

In summary, PNe known to contain close-binary nuclei are virtually all axisymmetric, with varying degrees of density contrasts. An unsolved question, of course, is whether the opposite is true, i.e., are *all* non-spherical PNe ejected from binaries? This hypothesis was debated at length at this workshop, but although it remains (in my opinion) highly plausible, it is still observationally unproven.

4.   PNe with Resolved Visual-Binary Nuclei

Wide binaries with initial periods less than $\approx 10^3$ days, but still wide enough for the primary to evolve to red-giant dimensions, will undergo a CE interaction and spiral down to much shorter periods, or coalesce (e.g., Yungelson et al. 1993). Those with larger initial separations will not enter into a CE, and in fact their separations will increase somewhat when the primary star ejects a PN. The widest of these latter binaries may be seen as resolved visual binaries.

We (Ciardullo et al. 1999) carried out a *HST* snapshot survey of PNNi with the Wide Field Camera 2, in order to search for the predicted popula-
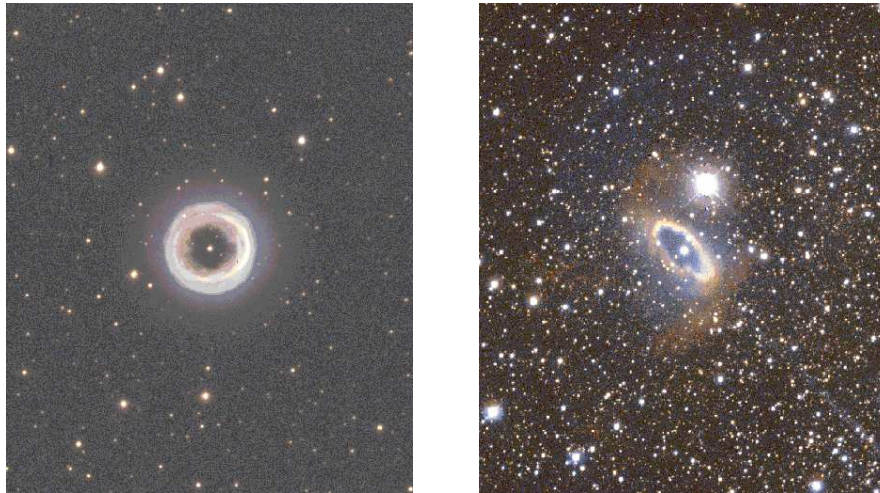
Figure 2.   Ground-based [O III]+Hα images of Sp 1 (**left**) and SuWt 2 (**right**), obtained with the Cerro Tololo 0.9-m. Both PNe appear to be rings with very low ratios of height to radius. The ring in SuWt 2 is viewed close to edge-on, and the central star is an eclipsing binary.

tion of resolved visual binaries in PNe. Out of 113 PNNi, a dozen probable or possible resolved nuclei were found. These binaries are extremely useful for finding accurate ($\pm 20\%$) distances to PNe, through main-sequence fitting of the companions. The results, as shown in Ciardullo et al., reveal that the previous statistical distances for PNe have been systematically overestimated, by up to a factor of ~ 2. However, in the context of this presentation, these very wide companions probably do not have major effects on the PN morphology. See, however, Soker (1999), who argues that the PN ejection process may be sufficiently leisurely for the orbital acceleration of the PNN during the ejection to lead to somewhat non-spherical morphologies.

5.   Other PN Phenomena that May Require Binaries

There are several other phenomena seen in PNe that may arise from binary-star interactions, although in general this hypothesis remains as yet unproven.

5.1.   Jets and Point-Symmetry

Jets, in all other astrophysical settings, are believed to result from outflows that are collimated by accretion disks. Thus it is a surprise to find jets in PNe, where one usually thinks of mass loss rather than accretion. Fig. 3 (left) shows diametrically opposed jets on either side of the nucleus of K 1-2. In a PN nucleus, formation of a disk probably requires mass transfer between binary companions, and thus K 1-2, where we know the PNN is a close binary, is instructive. A related phenomenon is point-symmetry, which is seen in a number of PNe; a spectacular example is shown in the *HST* image of NGC 5307, shown in Fig. 3 (right), in which nearly every blob and spiral-like feature has a counterpart on

the opposite side of the PNN. Point-symmetric structure could arise from an episodic jet from a precessing disk (e.g., Livio & Pringle 1997), but it is not yet known whether the nuclei of NGC 5307 or similar PNe are binaries.
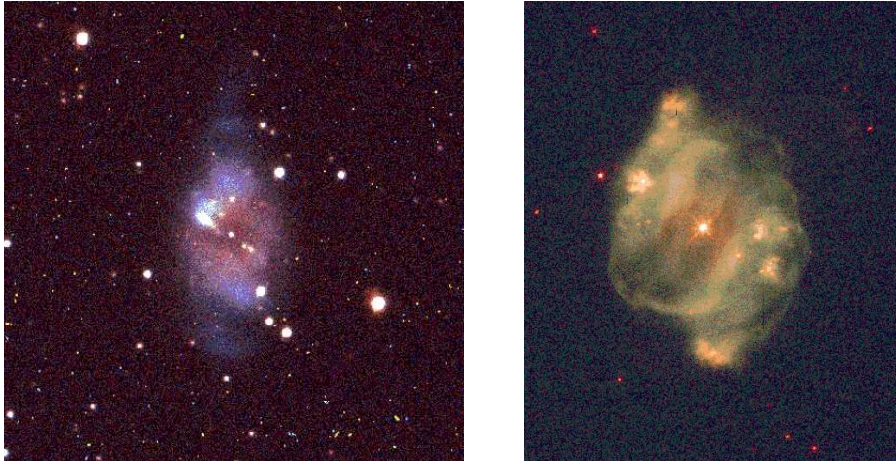

Figure 3.   (**Left**) Ground-based [O III]+Hα image of K 1-2, obtained with the Cerro Tololo 0.9-m. Note jets on either side of the close-binary nucleus. (**Right**) Broad-band ($V+I$) *HST* WFPC2 image of the point-symmetric PN NGC 5307, from the snapshot survey of Bond & Ciardullo.

5.2. Concentric Periodic Rings

HST imaging has revealed a remarkable new PN phenomenon: quasi-periodic concentric arcs in the halos of several bipolar PNe and proto-PNe. Examples include the PNe NGC 7027 (Fig. 4, left) and NGC 6543 (Fig. 4, right), and the proto-PNe CRL 2688 (the "Egg" Nebula; Sahai et al. 1998) and IRAS 17150$-$3224 (Kwok, Su, & Hrivnak 1998). In Fig. 4, I have processed both *HST* images through unsharp masking to enhance the visibility of the faint rings around the bright inner nebulae. More recent *HST* images reveal quasi-periodic *linear* features in the "Red Rectangle" (HD 44179; Cohen et al. 1999).

In NGC 7027, the characteristic spacing of the arcs is $\Delta r \simeq 3''$. If these features are due to modulated mass loss, the time interval between ejections is

$$\Delta t \simeq 575 \, \text{yr} \left(\frac{\Delta r}{3''}\right) \left(\frac{v_{\text{exp}}}{20 \, \text{km s}^{-1}}\right)^{-1} \left(\frac{d}{800 \, \text{pc}}\right).$$

The rings suggest that (a) the early outflow from the AGB progenitor was spherical, and later became aspherical when the densest portion of the PN was ejected, and (b) the early, spherical outflow was *episodic*.

The putative timescale of ~ 600 yr is too short to be due to thermal pulses in the AGB progenitor, and too long to be due to envelope pulsations. Other suggested origins of the periodicity include (a) a long-term amplitude modulation of envelope pulsations (Icke, Frank, & Heske 1992; Sahai et al. 1998); (b) the lifetime of individual giant convective cells (Schwarzschild 1975); (c) an
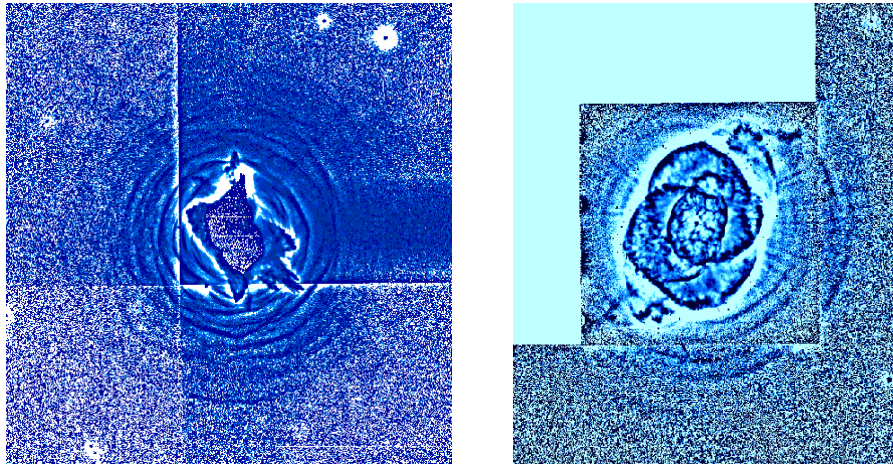
Figure 4.   *HST* Hα images of NGC 7027 (**Left**) and NGC 6543 (**Right**). Both images have been processed with unsharp masking, and reveal the faint, nearly circular and nearly regularly spaced system of arcs surrounding these nebulae.

instability in the radiation-driven gas/dust outflow (Morris 1992; Deguchi 1997) producing density waves in the dust; or (d) the influence of a binary companion. The last option is of course the one of interest in the present context. Harpaz, Rappaport, & Soker (1997) proposed that the rings could arise from the influence of a companion (even of planetary mass) in an eccentric orbit, but the number of PNe showing the phenomenon is now large enough that it seems unlikely that so many of the nuclei would have eccentric companions in 600-yr orbits. However, Mastrodemos & Morris (1999) have argued more recently that the rings could originate from spiral shocks produced by binary companions in circular orbits, and the predicted statistics for the frequency of occurrence of such companions (e.g., Yungelson et al. 1993) seem in rough accord with the statistics for the periodic rings.

5.3.   PNe in Globular Clusters

Here I ask the question "why are there PNe in globular clusters?" because I will show that there should not be any. Bond & Fullton (1999) have searched for post-AGB stars in the halo of M31, and show from the star counts that the post-AGB transition time through types F and A is $\approx 25,000$ yr for these remnants of low-mass ($\sim 0.8 M_\odot$) stars. Since the timescale for dissipation of a PN is thus shorter than the post-AGB evolutionary timescale for halo stars, *any PN should be gone by the time the central star becomes hot enough to ionize it*, and this argument should apply in globular clusters (GCs) as well as in galactic halos. However, Jacoby & Fullton (see Jacoby et al. 1997), in a complete survey of Milky Way GCs, found two new PNe, bringing the total number known in GCs to four.

One way to resolve the puzzle is to suppose that the PNe that are seen in GCs are descended from binary stars, in which the mass of one component was raised either by mass transfer, or by stellar coalescence. In this case, the remnant would have a higher mass than remnants from single stars, and would

evolve much more rapidly across the HR diagram, thus allowing it to ionize the PN while there is still time.

In order to test this hypothesis, we (Alves, Bond, & Zurek 1999) used *HST*'s WFPC2 to monitor the central star of the PN K 648 in the GC M15. In addition to the post-AGB lifetime argument summarized above, the known luminosity of the K 648 PNN places it on a post-AGB track of $0.58 M_\odot$ (Bianchi et al. 1995), considerably more massive than normal white dwarfs in GCs (Richer et al. 1997), again suggesting that the star has experienced a mass augmentation at some point in its past. Unfortunately, however, the star did not display any variability in our *HST* photometry, periodic or otherwise, on timescales of 45 min to about 10 days. But this does not rule out the hypothesis of binarity, since the PNN could still be a binary that is viewed pole-on, a binary with an orbital separation too large for significant heating effects, or a coalesced binary.

6.   Conclusions

I would like to conclude by asking the reader to consider two syllogisms:

<table>
<tr><td colspan="1">Planetary Nebulae</td><td>Ducks</td></tr>
<tr><td>1. Binaries eject axisymmetrical PNe.</td><td>1. Ducks quack.</td></tr>
<tr><td>2. Most PNe are axisymmetrical.</td><td>2. I quack.</td></tr>
<tr><td>3. Therefore most PNe are ejected from binaries.</td><td>3. Therefore I am a duck.</td></tr>
</table>

The syllogism on the left about PNe seems plausible, especially in the light of the circumstantial evidence I have presented in this paper. However, we should beware of the logical flaw in this syllogism, whose lack of rigor[2] is exposed in the syllogism on the right by changing the argument to one about ducks instead of PNe.

As often happens, the poet (Robert Frost) has the last word:

We dance 'round in a ring and suppose,
But the Secret sits in the middle and knows.

References

Alves, D. R., Bond, H. E., & Zurek, D. 1999, BAAS, 194, 85.18

Bianchi, L., Ford, H., Bohlin, R., Paresce, F., and De Marchi, G. 1995, A&A, 301, 537

Bond, H. E. 1995, In Asymmetrical Planetary Nebulae, Annals of the Israel Physical Society, 11, ed. A. Harpaz & N. Soker, 61

[2]See, however, `http://us.imdb.com/Title?0091225`

Bond, H. E., & Fullton, L. K. 1999, in Eleventh European Workshop on White Dwarfs, ed. J.-E. Solheim & E. Meistas (San Francisco: ASP), 439

Bond, H. E., & Livio, M. 1990, ApJ, 355, 568

Ciardullo, R., Bond, H. E., Sipior, M. S., Fullton, L. K., Zhang, C.-Y., & Schaefer, K. G. 1999, AJ, 118, 488

Cohen, M., Van Winckel, H., & Bond, H. E. 1999, in preparation

Deguchi, S. 1997, in Planetary Nebulae, IAU Symp. 180, ed. H. Habing & H. Lamers (Dordrecht: Kluwer), 151

de Kool, M. 1990, ApJ, 358, 189

Gatti, A. A., Drew, J. E., Lumsden, S., Marsh, T., Moran, C., & Stetson, P. 1997, MNRAS, 291, 773

Gatti, A. A., Drew, J. E., Oudmaijer, R. D., Marsh, T. R., & Lynas-Gray, A. E. 1998, MNRAS, 301, L33

Grauer, A. D., & Bond, H. E. 1983, ApJ, 271, 259

Han, Z., Podsiadlowski, P., & Eggleton, P. P. 1995, MNRAS, 272, 800

Harpaz, A., Rappaport, S., & Soker N. 1997, ApJ, 487, 809

Iben, I., & Livio, M. 1993, PASP, 105, 1373

Icke, V., Frank, A., & Heske, A. 1992, A&A, 258, 341

Jacoby, G. H., Morse, J. A., Fullton, L. K., Kwitter, K. B., & Henry, R.B.C. 1997, AJ, 114, 2611

Jeffries, R. D., & Stevens, I. R. 1996, MNRAS, 279, 180

Kwok, S., Su, K.Y.L., & Hrivnak, B. J. 1998, ApJ, 501, L117

Liebert, J., Tweedy, R. W., Napiwotzki, R., & Fulbright, M. S. 1995, ApJ, 441, 424

Livio, M., & Pringle, J. E. 1997, ApJ, 486, 835

Lutz, J., Alves, D., Becker, A. et al. (the MACHO Collaboration) 1998, BAAS, 192, 5309

Mastrodemos, N., & Morris, M. 1999, ApJ, 523, 357

Morris, M. 1992, in Mass Loss on the AGB and Beyond, ed. H. Schwarz (Garching: ESO), 60

Pollacco, D. L., & Bell, S. A. 1997, MNRAS, 284, 32

Richer, H. B., et al. 1997, ApJ, 484, 741

Sahai, R. et al. 1998, ApJ, 493, 301

Sandquist, E. L., Taam, R. E., Chen, X., Bodenheimer, P., & Burkert, A. 1998, ApJ, 500, 909

Schwarzschild, M. 1975, ApJ, 195, 137

Strassmeier, K. G., Hubl, B., & Rice, J. B. 1997, A&A, 322, 511

Soker, N. 1999, AJ, in press (astro-ph/9907305)

Walton, N. A., Walsh, J. R., & Pottasch, S. R. 1993, A&A, 275, 256

Yungelson, L.R., Tutukov, A.V., & Livio, M. 1993, ApJ, 418, 794